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WSMC-TR-91-02

Preliminary study of the admittance diagram as a useful tool in the design of stripline components at microwave frequencies

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ABSTRACT

It has been shown that the Admittance Diagram[1] along with the Quarter-wave Rule can be used in the design and characterization of Optical Thin Film coatings. However, this same tool may be utilized in the design and characterization of some microwave components as well. A simple design example of a Wilkinson Power Divider is presented to illustrate the utility of this optical technique for microwave circuit design and analysis.

1. BACKGROUND

Microstrip and stripline circuit design is unlike that used by most electrical engineers. This is due to the fact that elements at higher frequencies are often distributed rather than discreet. The operating parameters of a circuit or circuit element are found by utilizing different modeling tools than those used for standard electronics. Prior to the use of digital computers the Smith Chart was one of the main tools used for this purpose. The Smith Chart is useful in determining circuit behavior, but it is cumbersome to use and does not represent a very intuitive tool. The advent of the digital computer and advanced software packages capable of performing analysis of microwave circuits has replaced the Smith Chart as the main design tool. Computer algorithms may provide specific outputs concerning the circuit behavior, but they may not provide an intuitive understanding of the circuit behavior under excitation. This paper will introduce the use of a graphical tool developed for optical thin film analysis. This method of analysis will aid in the design of microwave circuits. It allows the designer to visualize the behavior of critical elements as well as optimize the circuit performance. Since one can easily construct a model based on impedance, the model presented here uses the admittance of a circuit element to determine certain parameters, which can be modeled just as easily. The admittance was chosen to retain continuity with this work and the work done for optical thin films.

The first section of this paper will present a brief introduction to both optical thin film and microwave theory. Next, there will be a discussion of the Smith Chart and the Admittance Diagram. The use of the Admittance Diagram will be shown by performing analysis on both the uncompensated and the compensated Wilkinson power dividers.

2. INTRODUCTION TO THE THEORY

A brief discussion of basic concepts is necessary in order to gain an understanding of what is to be accomplished in this study. An explanation of thin film filters (used at normal angle of incidence), the Smith Chart and the Admittance Diagram will also be addressed. The analysis assumes here that the optical thin films are used at a normal angle of incidence only, to model the behavior of microwave elements. For brevity, this will be assumed for all the optical analysis that follows. While only a graphical form of the Admittance Diagram will be discussed in this paper, exact values can be calculated utilizing the analysis discussed by Macleod[1] in his text. The utility of the graphical technique is the visualization it provides of circuit performance.

In general, when reflectance takes place in a medium of lower refractive index to a medium of higher refractive index there is a 180° phase shift. A 0° phase shift takes place in the opposite case, from higher to lower refractive indices. This is due to the fact that the reflectance at the top and bottom surfaces separate into two components of the light. The components recombine destructively for 180° phase shift and constructively for a 0° phase shift or multiples of 360°. Reflectance can be represented as

$$R = \rho^2 \tag{1a}$$

$$\rho = \frac{1-Y}{1+Y} \tag{1b}$$

where, ρ is the amplitude reflectance, R is the intensity reflectance and for a quarter wavelength thick thin film,

$$Y = \frac{y_1^2}{y_0 y_2} \tag{2}$$

where y_0, y_1, and y_2 are admittances of three different media in contact as shown in Fig. 1. Here, Y may be thought of as an equivalent admittance. We may interperate the action of the film as transforming the admittance y_2 into an admittance y_1^2/y_2 and this expression is known as the Quarter Wave Rule. This than gives us the refractive index relationship and should remain unchanged. The index of refraction n of a thin film layer is related to the admittance y of that layer by,

$$y = Y_f \ n, \tag{3}$$

where Y_f is the admittance of free space. This applies strictly to media where $\mu_r = 1$ and thus, in the optical region where this is satisfied equation (2) from above can be re-written for the refractive index N and takes the form

$$N = \frac{n_1^2}{n_0 n_2}\ , \tag{4}$$

Because of this simplification, optical admittances are usually quoted in units of the admittance of free space so that they have the same numerical value as the refractive index. Eq. (2) represents an example of a single layer of admittance y_1 on a substrate with admittance y_2 with incident media y_0. In Fig. 1 the indices of refraction may be replaced by their respective optical admittances. Y represents the equivalent admittance of the overall assembly. A single antireflecting thin film coating on a lens made of glass would have the same form with y_0, the admittance of air being equal to one.

The Smith Chart shown in Fig. 2 is used to calculate various properties of transmission lines. The impedance relations that the Smith Chart gives for a lossless line of different loads is important in this study and is represented by

$$X = \frac{1-Z}{1+Z} , \quad (5)$$

where Z is the impedance and is plotted in polar coordinates. The corresponding real and imaginary parts of X are read from the sets of orthogonal circles on the Smith Chart and will be discussed in more detail later. Notice the similarity between Eqs. (1b) and (5).

The Admittance Diagram also uses a graphical approach of the Smith Chart to relate the various properties of optical thin film layers. The Admittance Diagram is made up of half the complex plane which can be further divided into four regions that correspond to the quadrants of phase shift on reflection. Fig. 3 shows the contours which separate the quadrants. The arc or circular locus represents a single thin film layer. Procedures for calculating the equations for these contours are outlined in Macleod's text. The points connecting the arcs of circles correspond to the interface between the layers. In the case of the Wilkinson power divider shown in Fig. 4a and 4b these points would represent the interface between segments of transmission lines. The Wilkinson power divider which is a microwave stripline[2] component will be discussed later.

3.THEORY

The Smith Chart can be used to determine impedance and admittance with any load, standing wave ratio (SWR); and capacitive or inductive reactances of short circuited transmission lines or small sections of transmission lines called stubs[3]. For ease of calculation these parameters are normally determined for lossless lines. A similar situation exists for dielectric films where one assumes no absorption. However, it is also possible to calculate for lines with loss and thin films with absorption as well. For this study the most important application of the Smith Chart is the utilization of quarter wave stubs to match a load to a line. The Admittance Diagram may be utilized in a similar manner because it too uses a quarter wave matching technique. Therefore, the Admittance Diagram may be applied in a way similar to the Smith Chart as shown in Fig. 5. The following sections will explain some of the reasoning behind this concept.

3.1 Thin Film Filters

Stripline elements may be developed from quarter wave sections. This is a feature also common to optical thin films. It is not surprising then, that certain performance characteristics are also common. A designer for both stripline elements and thin film elements may wish to reduce or enhance reflected components; or phase match between elements; or produce an element that has broadband characteristics; or even sharpen the band characteristics with a spike filter. The use of the Admittance Diagram and the Quarter Wave Rule can be seen as an extension from quarter wave elements at optical frequencies to quarter wave elements at microwave frequencies.

We will begin by looking at one of the simplest optical thin film elements, a single layer used to match the admittance of a substrate to the admittance of the incident media taken to be air, as shown in Fig. 1. This is analogous to impedance matching. Here light is incident on an planar optic made of glass coated with an optical thin film. The light reflected at the top and bottom layer(s) of an assembly must cancel to behave as an antireflective coating. From Eqs. (1a) and (1b) this means that $1 - Y = 0$, or

$$y_1^2 = y_0 \, y_2 , \quad (6)$$

where the value of the admittances are, for example $y_0 = 1$ for air and $y_2 = 1.52$ for glass. Therefore, the thin film admittance should be between the admittance of air and the substrate to accomplish complete cancellation, for this example $y_1 = 1.23$. The optical thickness of the film should be one quarter wavelength to insure 180° phase shift. In other words, the total difference in the phase shift between the two beams should be equal to one half wavelength.

3.2 Multilayer Thin Film Stack

A multilayer, known as a quarter wave stack, is another thin film filter. It consists of quarter wave thin film layers whose indices are stacked alternately high and low in the assembly. Upon reflection, the high index layer will not experience a phase shift, while light in the lower index layers will have a 180° phase shift. For enhanced reflectors this results in a constructive recombination at the front surface. The reflectance of the multilayer depends on the wavelength and the number of high and low index layers. The quarter wave stack technique is commonly used in the design of thin film filters. Similarly, a series or stack of quarter wave stripline segments may be utilized with this technique to develop a model for the design of a Wilkinson Power Divider or similar microwave components.

4. QUARTER WAVE AND HALF WAVE THIN FILM LAYER REPRESENTATION ON THE ADMITTANCE DIAGRAM

A brief discussion on how both quarter wave elements or the combination of quarter wave layers forming half waves elements (sometimes called absentee layers) are used to produce multilayer assemblies, will now be discussed. Half-wave layers are called absentee layers because at the design wavelength, the light reflected from the bottom surface of the layer has undergone a 360° phase shift with respect to the incident light reflected from the top surface, that is apart from any phase shift from the reflection at the boundarys themselves. This results in the suppression of any interference effects and the effective elimination of the halfwave layer. It is therefore correct and convenient to omit half wave layers for ease of computing the assembly properties.

The addition of an odd number of quarter wave layers[1] with admittance y alters the equivalent admittance from Y of the assembly to y^2/Y. By extension, a stack of five quarter wave layers of different materials can easily be calculated as

$$Y = \frac{y_1^2\, y_3^2\, y_5^2}{y_2^2\, y_4^2\, y_{sub}} \quad , \tag{7}$$

or y_i for the optical admittance of each i^{th} layer, where i represents layers 1 through 5, and y_{sub} is the admittance of the substrate.

Assemblies of quarter and half wave layers are often used in the design of optical thin films because of the simplicity of the calculations involved. It is only necessary to specify the number of quarter or half waves and the wavelength. Usually, the materials for quarter wave optical thicknesses are specified as H for a High index of refraction, M for an intermediate index and L for a Low index. Half waves are represented by HH, MM, or LL. For example, a multilayer assembly of high and low indices consisting of quarter wave layers on a glass substrate would be represented by

Air | HLHLH | Glass

and is shown in Fig. 6 . A multilayer containing some quarter wave and half wave layers (absentee layers) might be represented with the indicated layers effectively canceling at the design wavelength as follows

Air | HLHHLHLH | Glass ,

At the wavelength for which all H,L are quarter waves this reduces to just Air | LH | Glass, since the absentee layers can be neglected. Fig. 7 shows the equivalent Admittance Diagram with the absentee layers removed.

The Admittance Diagram will be use to design and analyze the quarter wave sections of the Wilkinson Power Divider stripline model in the following section.

5.THE WILKINSON POWER DIVIDER

The Admittance Diagram, developed by Macleod uses a graphical approach not unlike the Smith Chart to relate the various properties of optical thin film layers although the emphasis is on admittance rather than amplitude reflection coefficient. The quarter wave matching technique utilized by the Smith Chart to design stripline circuits is similar to that of the Admittance Diagram for the design of quarter wave optical thin film coatings. This technique will be illustrated by designing a Wilkinson power divider. A stripline model will be developed for the power divider. The results will be analyzed using the Admittance Diagram. The advantage here is that the Admittance Diagram allows a more visual method of analyzing the circuit performance prior to fabrication.

The Wilkinson power divider is used as a broadband stripline circuit for power division which provides equal phase characteristics and isolation between the output ports. This three port device presents a matched termination at the input (sum) port 1, when the other ports are match terminated. The power at the input port 1 of this binary power divider splits equally among the two other ports 2 and 3 as shown in Fig. 8a and 8b.

Either of the output ports 2 or 3 may be isolated when power is delivered to one of them, while port 1 and the other remaining port are match terminated. The sum port will then receive power with some loss.[4] The power divider used in this example consists of quarter wave sections with characteristic impedances of 70.7Ω as shown in Fig. 8b. The Quarter Wave Rule was applied to verify the impedance values of the uncompensated and compensated dividers shown in Fig. 4a and 4b. The quarter wave rule comes from the reflectance Eqs. (1a), (1b) and (2). Letting R=0 for zero reflectance gives

$$y_1 = \sqrt{y_0 \times y_2} \quad . \tag{8}$$

The Quarter Wave Rule can be represented in terms of transmission line impedances for the power divider as

$$Z_{p_1} = \sqrt{Z_0 \times Z_{p_2}} \quad , \tag{9}$$

where, Z_{p1} is used to impedance match Z_0 to Z_{p2} and is the parallel combination of the two 70.7Ω quarter wave impedances at the junction; Z_0 is the characteristic impedance of the power divider transmission line of 50Ω and Z_{p2} is the parallel combination of the two output port impedances which results in an impedance of 25Ω shown in Fig. 9.

The compensated power divider improves the performance by the addition of a quarter wave transformer in front of the power division junction[5] as seen in Fig. 4b. The result is a shift in the impedance levels and a broader frequency band as shown in Fig. 10.

It can be seen that no power is dissipated in R_x, shown in Fig. 8, when Z_0 terminates ports 2 and 3. Also the energy is at the same potential and Port 1 has an input impedance of Z_0. If the source is then placed on port 2 for example with matched loads (Z_o) on ports 1 and 3, even and odd mode analysis is needed to give the characteristic ABCD matrix involving the voltages and currents for each of the modified even and odd mode circuit models to be analyzed.[4,6] Using this analysis the value of the difference resistor R_x was found to be equal to $2Z_o$ or 100Ω.

5.1 Verification of Power Divider Impedance Values

The uncompensated power divider design was verified using the Quarter Wave Rule as follows

$$Z_{p_1} = \sqrt{50\Omega \times 25\Omega} = 35.35\Omega \; . \tag{10}$$

The objective is to match a 50Ω line to a 25Ω line. A quarter wavelength transmission line segment with an impedance of 35.35Ω placed between the 50Ω and 25Ω segments will correctly match the two lines together.

It is desirable to have a visual method of representation to analyze these results. The Admittance Diagram accomplishes this. Using Eq. (2) for plotting thin film layers on the Admittance Diagram and converting to terms of impedance gives

$$Z_{p_2} = \frac{Z_{p_1}^{\,2}}{Z_o} . \tag{11}$$

For this example

$$Z_{p_2} = \frac{(35.35\Omega)^2}{50\Omega} = 25\Omega \; . \tag{12}$$

In order to represent these results in terms of optical admittance it is convenient to normalize y_o to one by dividing by 25Ω. In other words, use Eq. (11) but let $y_o = Z_{p_2}/Z_{p_2}$, $y_1 = Z_{p_1}/Z_{p_2}$ and $y_{sub} = Z_o/Z_{p_2}$, which gives

$$y_o = \frac{y_1^{\,2}}{y_{sub}} = 1 \; . \tag{13}$$

For zero reflectance $R = 0$ and with $y_o = 1$, we have

$$y_1 = \sqrt{y_{sub} \times y_o} = \sqrt{2} \; , \tag{14}$$

where, as stated above, $y_{sub} = 50\Omega/25\Omega$.

For a low index layer on a glass substrate this would be represented as,

air | L | glass

Therefore, on the Admittance Diagram, shown in Fig. 11, the transition layer is represented beginning at the substrate with admittance 2 (y_{sub}) and continuing clockwise through the quarter wave layer to 1 (y_o) as shown in Fig. 11. In terms of impedance, the transformer matching transition begins at the 50 Ω segment and continues through the 35.35 Ω segment to the 25 Ω segment of transmission line, shown normalized in Fig. 9.

For the compensated power divider shown in Fig. 4b, a quarter wavelength segment with an impedance of 42 Ω was added between the junction and the input port. The addition of this segment requires a change in the impedance values of the quarter wavelength branches from 70.7 Ω to 59.4 Ω. In order to verify these values, the parallel combination of the 59.4 Ω and 50 Ω branches were considered. A quarter wave transformer model was then designed and is shown in Fig. 12.

In the previous example it was shown that the center of the 50 Ω | Z_{p1} | 25 Ω line was 35.35 Ω. For convenience, an artificial impedance point of 35.35 Ω was constructed for the compensated power divider. Hence, for this case, the 50 Ω segment is to be matched to the 35.35 Ω segment and the 25 Ω segment is to be matched to 35.35 Ω segment as shown in Fig. 12. For this analysis, any reasonable artificial impedance point can be chosen and the 50 Ω and 25 Ω impedance values matched to it. The 29.7 Ω segment is just the parallel combination of the two 59.4 Ω segments shown in Fig. 4b. The Quarter Wave Rule can then be used to verify the impedance values for the multi-segmented power divider as shown below

$$Z_{p1} = \sqrt{50\Omega \times 35.35\Omega} = 42.04\Omega \quad . \tag{15}$$

where 50 Ω is matched to the artifically constructed impedance point 35.35 Ω and

$$Z_{p2} = \sqrt{35.35\Omega \times 25\Omega} = 29.7\Omega \quad , \tag{16}$$

where the 25 Ω point is matched to the artifically constructed impedance point 35.35 Ω and $y_1 = Zp_2/Z_{p3}$, $y_2 = Zp_2/Z_{p3}$. The normalized Admittance Diagram for the compensated power divider is shown in Fig. 13.

5.2 Broad Frequency Band Verification

To verify that the addition of the quarter wave section in the front of the power division junction does indeed broaden the frequency response, analysis of the compensated Wilkinson Power Divider using the normalized impedance. will now be performed with the aid of the Admittance Diagram. Shown in Fig. 13 was the Admittance Diagram for the compensated power divider. For this analysis, let us pick a design frequency ω_d of approximately 7.5 GHz. This represents a wavelength λ_d of approximately 40 cm. A quarter wave strip is 10cm long, ignoring wavelength shifts in the stripline due to material properties. For actual stripline circuits, the impedance is varied by strip thickness and width[2]. Normalization was performed by dividing by 25 Ω. Fig. 13 shows that the high impedance of the base segment starting at the 2.000 (50 Ω /25 Ω) point is matched to the low impedance segment ending at the 1.000 (25 Ω/25 Ω) point by two quarter wave segments. These segments match the center 1.414 (35.35 Ω/25 Ω) point to the outer points. Using Eq. (11) the first segment was calculated to have a normalized value of 1.682 (42 Ω/25 Ω) and performs the match from the 2.000 point to the 1.414 point. Similarly, the second segment was calculated to have a normalized value of 1.189 (29.7 Ω/25 Ω) and performs the match from the 1.414 point to the 1.000 point.

Here, both of the clockwise circles are 10cm long because, as stated earlier, they are quarter wave segments *at the design wavelength*, λ_d = 40cm. What we want to know is, "What happens when we are *not* at the design wavelength due to a shift in signal input frequency? " For this example, let us say that the excitation wavelength has shifted to λ_e = 36cm. This represents a quarter wave of 9cm. Shown in Fig. 14 is the Admittance Diagram for the same stripline circuit as before but with a *shorter* excitation wavelength. At first glance, one might expect the semicircles to be shorter for a shorter wavelength. However, remember that the stripline circuit was designed for a quarter wave of 10cm. The Admittance Diagram shows the circuit with the wavelength in use, which is now 9cm. Hence, a 9cm segment would be represented by one complete clockwise semicircle. Our segment is 10cm long. This is represented by the clockwise extension of the semicircle beyond the horizontal axis due to the additional 1cm section. It should be noted here that the length of the additional arc of the circle is not a linear function of the segment length. The eighth wavelength point is shown in Fig. 14.

Since the segment of the first semicircle is too long, due to the additional 1cm segment, we do not get a good match to the center point at our shifted wavelength. We see that the next semicircle, a consequence of the second segment, begins at the end of the previous semicircle, and is also too long for the same reason. The quarter wave is 9cm and our segment is 10cm long. The end result is that each additional segment cancel each other and compensation is seen to take place. The second semicircle intersects the horizontal axis very close to the desired value of 1.000. The shift in the end point of the second semicircle is primarily along the horizontal. This indicates that only a slight phase shift will be introduced. It may also be noted that at this new wavelength, the intersection point of the two semicircles is above the horizontal axis and here, where it is not important, there is a phase shift.

Similar arguments could be made if we were to now pick a *longer* excitation wavelength λ_e = 44cm, with a quarter wave of 11cm. In that case the first semicircle would fall short of reaching the horizontal axis due to the 1cm difference between the design quarter wave and the signal quarter wave shown in Fig. 15. The second semicircle would also be short, but since it begins below the horizontal axis it also intersects the horizontal axis very close to the design impedance point, again showing that the original design is compensated for longer wavelengths. The frequency band of operation has indeed been broadened using this technique. While the exact values for center and final impedance points have not been calculated, they can be calculated by the interested designer. The important point here is to recognize how easy it is to perform simple analysis that provides a high degree of insight into the basic performance of a circuit.

The Wilkinson power divider discussed previously can also be improved by the addition of a half wave segment, or half wave flattening layer. A broader frequency band and zero reflectance may be accomplished by adding two quarter wave segments of higher impedance (Z_H = 75Ω for example). However, this alternate design is beyond the scope of this paper and will be addressed in subsequent publications.

6. CONCLUSION

A correlation between the optical thin film method of design and the microwave method of design has been shown for the simple structures presented. The use of the Admittance Diagram in the design of optical thin films involves a model consisting of stacks or segments of single dielectric layers. The Quarter Wave Rule and the Admittance Diagram have been used in a similar manner to design certain stripline devices which were modeled as quarter wavelength segments and parallel branch segments connected in a continuous transmission line.

It has been shown that broadband techniques used in optical thin film design may also be applied to microwave components with comparable results. It is reasonable to expect that many microwave components may be further improved by using other techniques from optical thin film coating designs. For example, one may use the addition of a half wave flattening layer to produce a broader frequency band element while maintaining zero reflectance. Experimental analysis must still be performed on more complex devices (for example low-pass, high-pass, and band-pass filters, directional couplers, unequal power dividers and various transmission and reflection devices) to verify to what extent this technique may be used.

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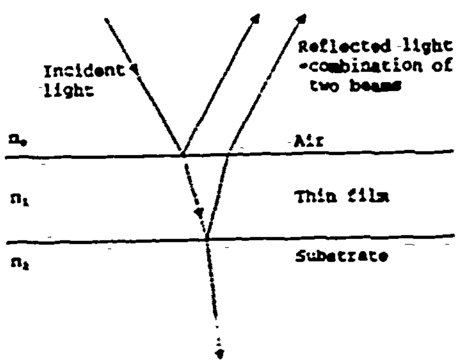

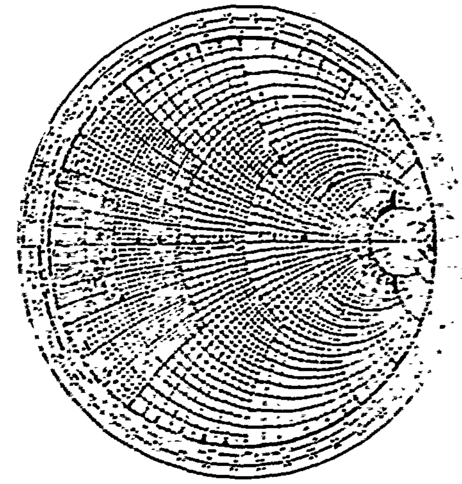

Fig. 1. Shown is a single optical thin film layer with index of refraction, n_1 on a substrate with index of refraction n_2. The incident media has an index of refraction of n_0. Light is incident on the thin film at zero degrees angle, but is presented with finite angle for clarity. The two reflected beams from the top and bottom surface recombine coherently.

Fig. 2. The Smith Chart consists of loci of constant resistance and reactance plotted in the complex plane where w = u+iv on a polar diagram. One can find the impedance transformed along a transmission line or relate the standing wave ratio or the reflection coefficient to the impedance. It allows one to understand the behavior of complex impedance matching techniques.[3]

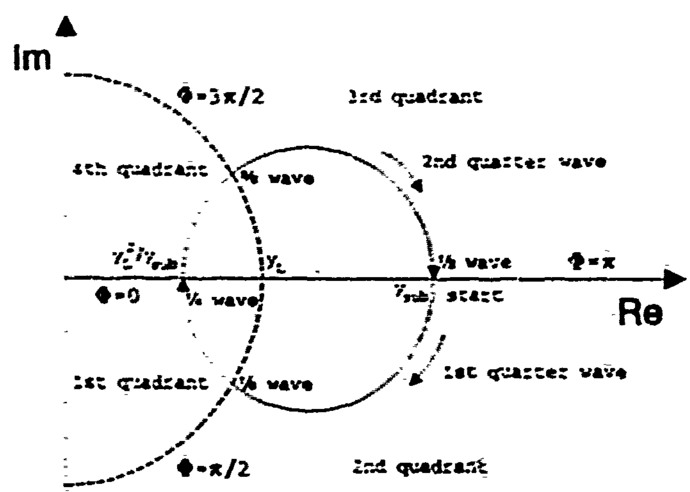

Fig. 3. The Admittance Diagram is shown for a single thin film layer deposited on a substrate at a design wavelength of λ_d. The deposition of the layer begins on the substrate y_{sub} on the real axis. As depositions proceeds, the circle continues counter clockwise intersecting the other circle that is centered on the imaginary axis with radius y_L. At this point the optical path is $\lambda/8$ and light would have a phase shift of $\phi = \pi/2$. As deposition continues, the circle intersects the real axis at y_L^2/y_{sub}. The optical thickness is one quarter wave and the phase shift for the light is $\phi = 0$. As more material is deposited on the substrate the thickness of the layer increases passing the three eighths wave thickness with a phase shift of $\phi = 3\pi/2$ and finally intersects the real axis at the starting point but with one half wave layer and a phase shift of $\phi = \pi$ for the design wavelength λ_d. Shown are the contours that separate four quadrants. The 1st and 4th quadrants are inside the boundary of the circle with radius y_L. The 2nd and 3rd quadrants are outside the same boundary.

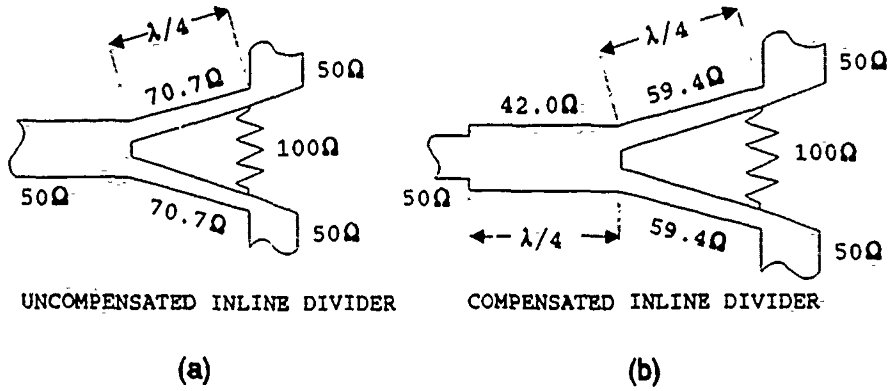

Fig. 4a. The Uncompensated Wilkinson Power divider with 70.7 Ω quarter wave section; 100 Ω resistor Rx and 50 Ω characteristic impedance of the line. Fig. 4b. The compensated power divider. The quarter wave 42 Ω segment allows for a broader frequency band.[5]

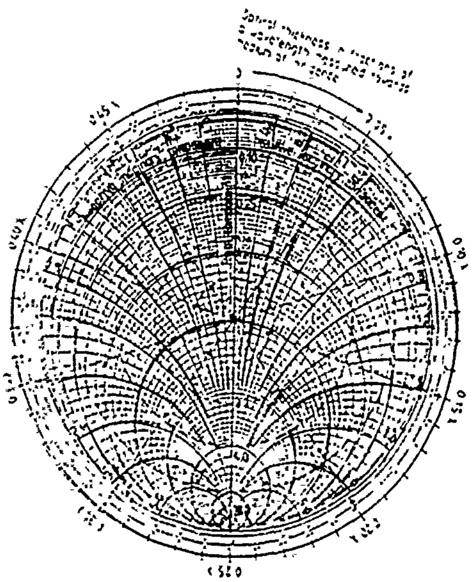

Fig. 5. Admittance Diagram applied to the Smith Chart. The solid circles represent constant real and imaginary parts of the admittance. The broken circles are constant amplitude of the reflectance coefficient with the outside solid circle equal to 1.0. The optical thickness is measured in fractions of a wavelength towards the medium of incidence.[1]

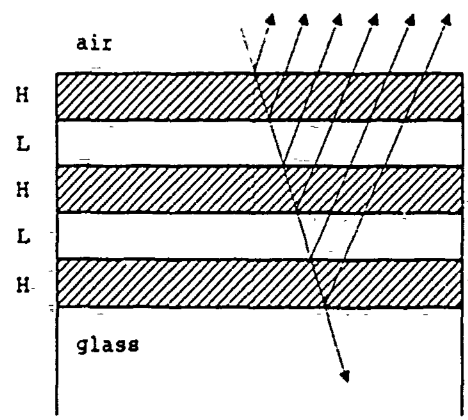

Fig. 6. Assembly of five quarter wave layers. The combination of the multilayer and the substrate can be represented by a single equivalent admittance Y.

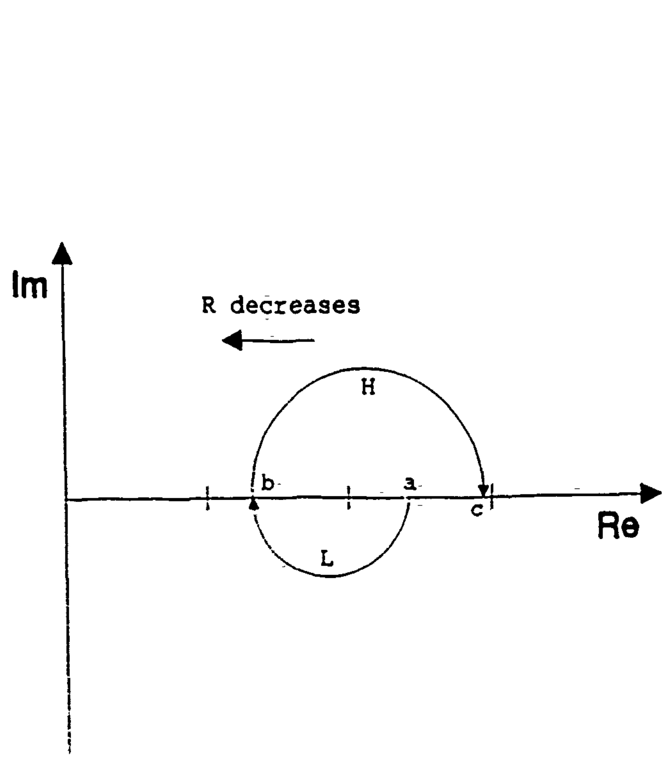

Fig. 7. Admittance Diagram for a Low-High index layer configuration. The closer the effective admittance comes to the input admittance, in this case 1 for air, the lower the reflectance R. The addition of the two layer stack is seen to increase the reflectance because the effective admittance is now greater than the substrate admittance. The value of the admittance at the starting point a is just y_{sub} and proceeds clockwise for the low admittance layer L to point b giving y_L^2/y_{sub}. The admittance then continues in a clockwise direction for the high index layer H ending at point c the result is the effective admittance $Y = y_H^2\, y_{sub}/y_L^2$.

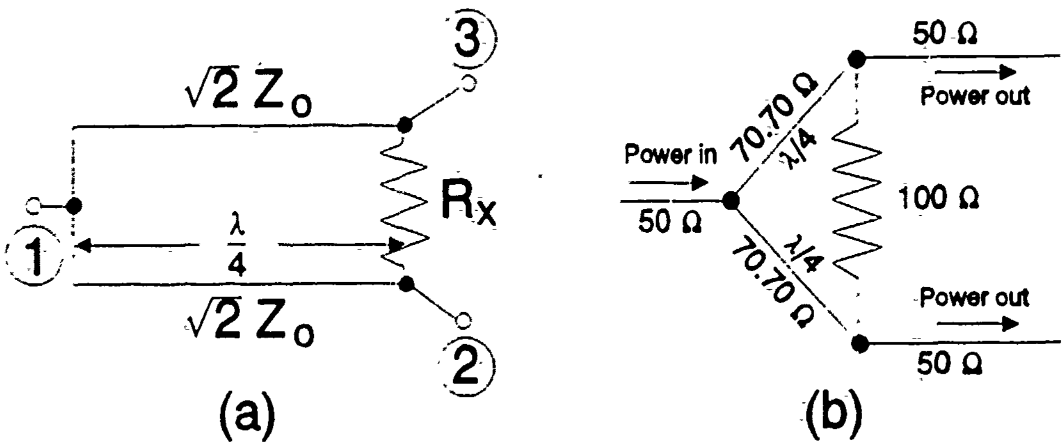

Fig. 8a. The binary power divider is shown with port 1 as the input, ports 2 and 3 the output ports and Rx known as the difference resistor. Fig. 8b shows the schematic for the Wilkinson power divider with characteristic impedance of the line equal to 50 Ω on the input and output lines and 100 Ω for the difference resistor. Both dividers consist of quarter wave segments.[4]

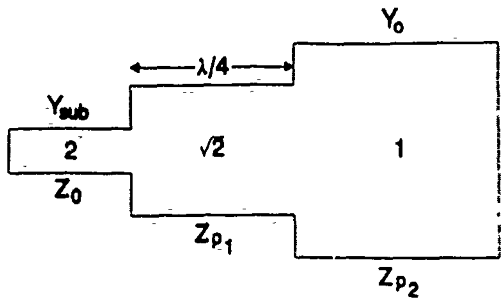

Fig. 9. The Transformer Model of the Wilkinson Power Divider using the Quarter Wave Rule. The parallel combination of impedances are represented as single transmission line segments. Where $Z_0 = 50\Omega$, $Z_{p1} = 35.35\Omega$ and $Z_{p2} = 25\ \Omega$.

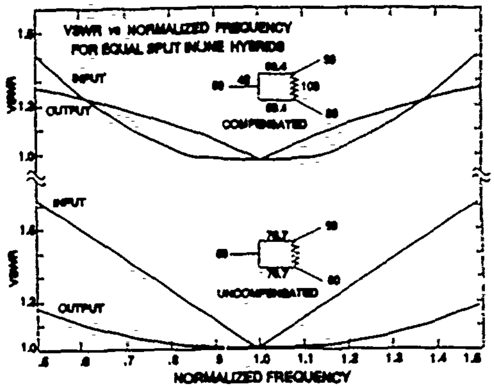

Fig. 10. Shown is the VSWR versus Normaliz.d frequency for the uncompensated and compensated Wilkinson power dividers.[5]

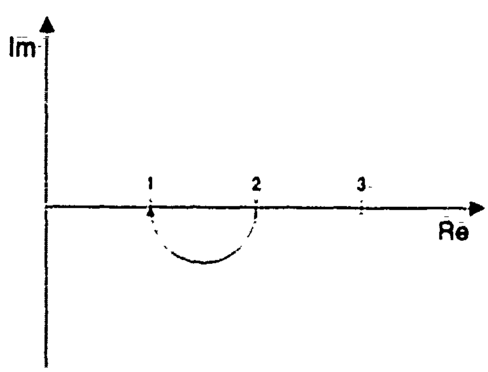

Fig. 11. The Admittance diagram for the uncompensated power divider. The semicircle begins at the substrate with normalized admittance $y_{sub} = 2$ and continues clockwise to the normalized output admittance $y_0 = y_L^2/y_{sub} = 1$, where $y_L = 1.414$ is the admittance of the quarterwave layer.

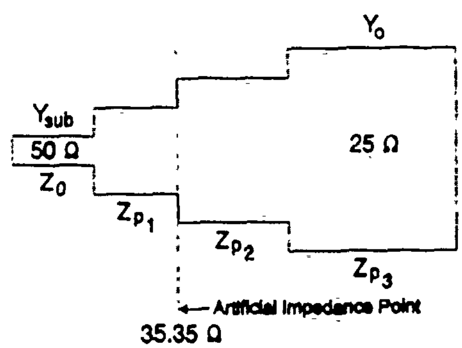

Fig. 12. The transformer model for the compensated power divider. The $Z_{p_1} = 42\ \Omega$ and $Z_{p_2} = 29.7\ \Omega$ segments are matched to the artificial impedance point of 35.35Ω.

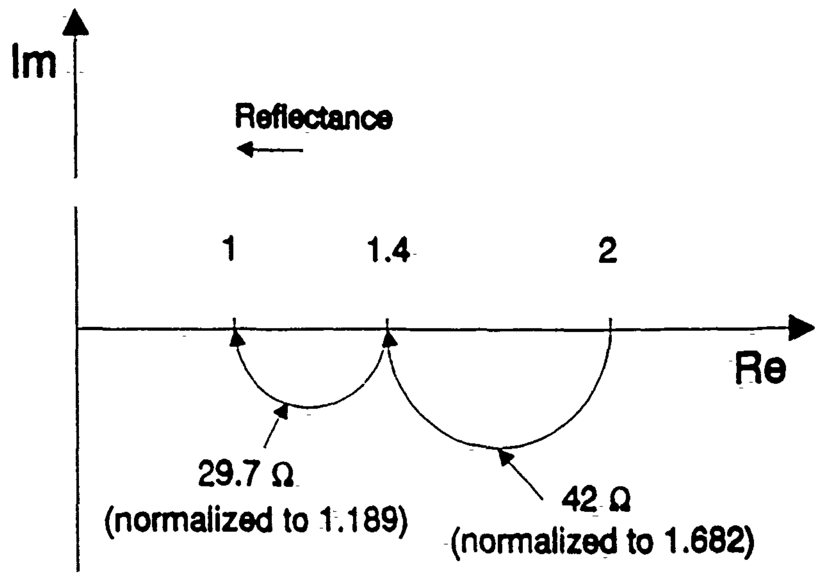

Fig. 13. The Admittance Diagram for the compensated power divider. The admittance begins at $y_{sub} = 2$ and continues clockwise for the 42Ω transmission line segment to admittance $y_M^2/y_{sub} = 1.414$. The admittance continues for the 29.7Ω line segment resulting in an equivalent admittance of $y_L^2\, y_{sub}/y_M^2 = 1$. Where $y_{sub} > y_M > y_L$.

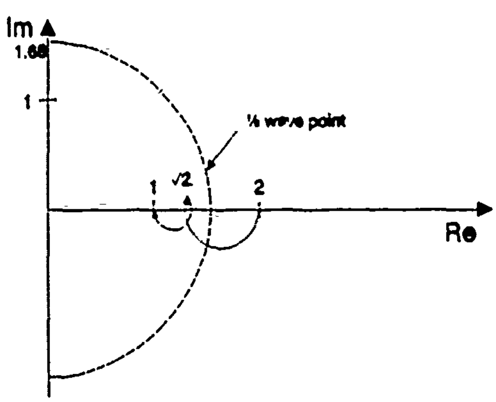

Fig. 14. The Admittance Diagram for the compensated power divider designed for λ_d = 40cm but used at excitation wavelength λ_c = 39cm.

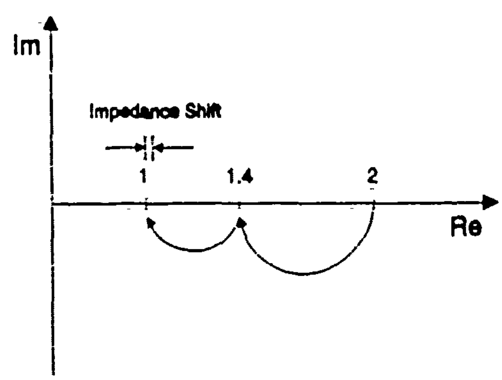

Fig. 15. The Admittance Diagram for the compensated power divider designed for λ_d = 40cm but used at excitation wavelength λ_e = 44cm.